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Reliability analysis of mechanical drives of sucker-rod pumps accounting for unrecoverable failures

Analiza niezawodności napędów mechanicznych pomp żerdziowych z uwzględnieniem uszkodzeń nienaprawialnych

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ABSTRACT: This study examines the impact of unrecoverable failures on the reliability of sucker-rod pump drives. As a critical component of sucker-rod pumps, the mechanical drive significantly influences the reliable operation of the entire system. While many failures can be addressed through repair, unrecoverable failures may occur due to damage, wear, or aging of system components. In this work, drive failures are modelled through three processes: recoverable failures characterized by failure and recovery rates, unrecoverable failures requiring system decommissioning, and aging, in which continued operation becomes economically unfeasible. A Markov model is employed to evaluate reliability under the assumption of exponentially distributed failures and recoveries. The analysis begins with a single drive component—the motor—and extends to multi-component drive systems. Analytical solutions via the Laplace transform are complex; therefore, Kolmogorov's system of differential equations was solved numerically using MATLAB. The results demonstrate that unrecoverable failures significantly affect system reliability, highlighting the necessity of accounting for such failures when assessing reliability indices and planning replacements for the drive or its individual components.

Keywords: sucker-rod pumps, drive systems, unrecoverable failures, reliability indicators, failure rate, Markov model.

STRESZCZENIE: W niniejszej pracy przeanalizowano wpływ uszkodzeń nienaprawialnych na niezawodność układów napędowych pomp żerdziowych. Napęd mechaniczny, jako jeden z kluczowych elementów pompy żerdziowej, ma istotny wpływ na niezawodność pracy całego układu. O ile wiele uszkodzeń można usunąć w drodze naprawy, o tyle uszkodzenia nienaprawialne mogą wynikać z awarii, zużycia lub starzenia się elementów systemu. W artykule uszkodzenia napędu opisano za pomocą trzech procesów: uszkodzeń naprawialnych, charakteryzowanych intensywnością uszkodzeń i intensywnością odnowy, uszkodzeń nienaprawialnych wymagających wycofania systemu z eksploatacji oraz procesu starzenia, w którym dalsze użytkowanie staje się ekonomicznie nieuzasadnione. Do oceny niezawodności zastosowano model Markowa, przyjmując wykładniczy rozkład czasów do wystąpienia uszkodzeń oraz czasów odnowy. Analizę rozpoczęto od pojedynczego elementu napędu, tj. silnika, a następnie rozszerzono ją na wieloelementowe układy napędowe. Ponieważ rozwiązania analityczne z wykorzystaniem transformaty Laplace'a są złożone, układ równań różniczkowych Kołmogorowa rozwiązano numerycznie w środowisku MATLAB. Uzyskane wyniki wskazują, że uszkodzenia nienaprawialne istotnie wpływają na niezawodność systemu, co potwierdza konieczność ich uwzględniania zarówno przy wyznaczaniu wskaźników niezawodności, jak i przy planowaniu wymiany napędu lub jego poszczególnych elementów.

Słowa kluczowe: pompy żerdziowe; układy napędowe; uszkodzenia nienaprawialne; wskaźniki niezawodności; intensywność uszkodzeń; model Markowa.

Introduction

Sucker-rod pumps are the most common type of pump designed for lifting fluid from oil wells. The drive of a sucker-rod pump is a pumping unit, also known as a rocking machine, usually consisting of an electric motor, V-belt drive, gear reducer, and double four-bar mechanism (Takacs, 2015; Chalabi et al., 2021 and 2022). The mechanical drive is one of the critical subassemblies of sucker-rod pumps (Figure 1), the technical level of which plays a significant role in the reliable operation of the entire equipment.

In the literature on reliability, technical systems, including oilfield equipment, are usually divided into two groups: repairable systems and unrepairable systems (DIN 40041,

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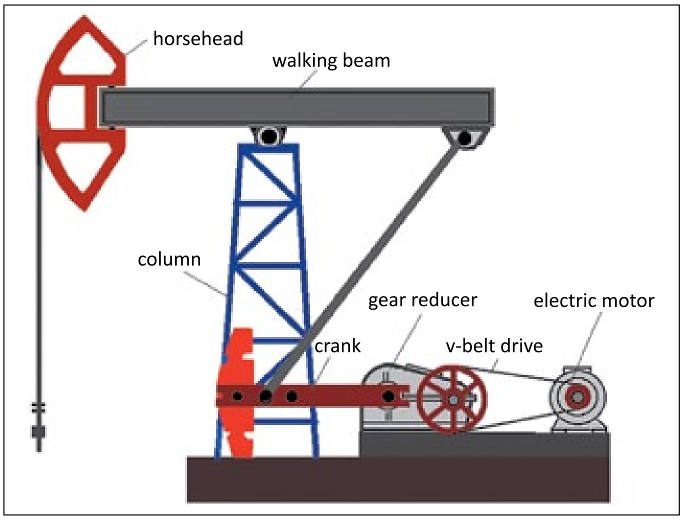

Figure 1. Sucker-rod oil pumping unit

1990; Bertsche, 2008; Babayev et al., 2015; Birolini, 2017). In the case of unrepairable systems, only unrecoverable failures occur. Conversely, in the case of repairable systems, mostly recoverable failures occur, which can be eliminated by repair. Nevertheless, repairable systems are not immune to unrecoverable failures, resulting in the system being permanently taken out of service (DIN 40041, 1990; DIN 31051, 2012; Tschalabi, 2019). During the operation of a technical system, failures may occur that can no longer be repaired. Unrecoverable failures can result from production-related causes (incorrect design, defective components, etc.) or operational causes (poor operating conditions, human error, poor maintenance, aging, corrosion, etc.). These failures and their effects on reliability parameters can be very significant for some repairable systems.

The existing literature, reliability analyses of repairable systems are primarily based on data regarding recoverable failures (Ushakov and Harrison, 1994; Bertsche, 2008; Strunz, 2012; Härtler, 2016; Birolini, 2017). In reality, however, random failures may also occur during operation that cannot be recovered for various reasons (DIN 40041, 1990; DIN 31051, 2012). For some systems, the proportion of unrecoverable failures can be significant, and the components of sucker-rod pump drives are among such systems. Additionally, failures often occur after prolonged operation due to fatigue and wear of components, and the system loses profitability due to aging. In such cases, repairing the failed unit is economically unjustifiable, and it is ultimately retired from service (DIN 31051, 2012). Therefore, unrecoverable failures and the aging process must be also taken into account in reliability analyses of repairable systems.

For a more accurate assessment of repairable technical systems, both recoverable and unrecoverable failures should be analysed in detail. These two types of failures differ in nature, causes, and impact on reliability characteristics. From a manufacturer's perspective, precise estimation of reliability parameters is essential for evaluating product quality, identifying weaknesses, and implementing appropriate improvements. In this study, the reliability analysis focuses on a specific viewing unit, excluding replacement after unrecoverable failure.

Problem statement

The approach in this article considers the evaluation of reliability parameters of repairable systems through three distinct processes, as illustrated in Figure 2. In the first process, failures can be remedied by repair, characterized by the recoverable failure rate $\lambda_r(t)$ and repair rate $\mu(t)$. The second process addresses unrecoverable failures, with failure rate $\lambda_u(t)$; no repair is planned in this case, and the system is removed from service. The third process accounts for aging, characterized by rate $\lambda_a(t)$, in which systems are taken out of service solely due to economic unprofitability.

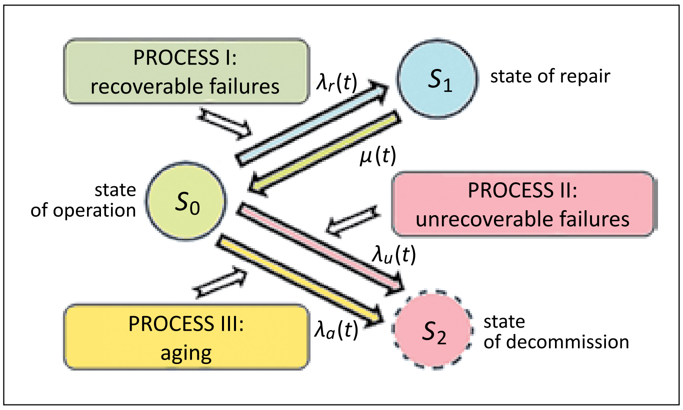

Figure 2. Processes and state graphs for repairable technical system

Reliability analysis for a single component

Evaluating the reliability of individual components of a technical system is often of critical importance, particularly when each component is supplied by different manufacturers. This study considers the reliability assessment of a single component using the example of an electric motor, a key part of sucker-rod pump drives. Electric motors are repairable technical systems, meaning their operability can usually be restored through maintenance. However, in some cases, failures may occur that require the motor to be taken out of service. Examples of such failures include catastrophic damage to the induction coils or extensive wear of critical components.

In the simplest case, reliability analysis of a technical system can be performed using a Markov model if the distributions of failures and repairs follow an exponential law. The Markov state diagram for individual components, such as an electric motor, accounting for unrecoverable failures, is shown in Figure 3a. As illustrated, the component can exist in three states (Figure 3b). In state S_0, the motor is operational, with probability $P_0(t)$. In state S_1, the component is under maintenance, with probability $P_1(t)$; this state includes activities such as inspection, repair, and improvement (Moubray, 1997; DIN 31051, 2012). In state S_2, with probability $P_2(t)$, the component is completely inoperative, and repair is technically or economically unfeasible, leading to permanent decommissioning.

Since in this case the failure and repair rates are constant, $\lambda_r(t) = \lambda_r$, $\mu(t) = \mu$, $\lambda_u(t) + \lambda_a(t) = \lambda_d = \text{const}$ is assumed.

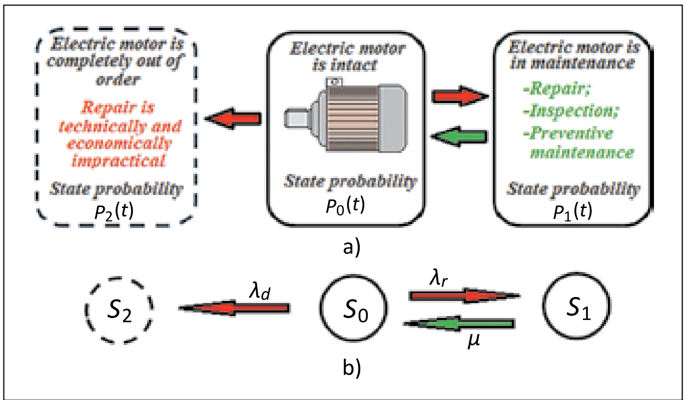

Figure 3. The states (a) and Markov graphs (b) for electric motor

The probabilities of states can be found by solving a system of Kolmogorov differential equations (Storm, 2001; Bertsche, 2008; Birolini, 2017). To compile these equations, the probabilities of possible state changes are taken into account. This change is additively composed of transition probabilities. Each transition probability is determined by multiplying the probability of the state by the corresponding the intensity of the transition. In this case, the arrows coming from the state become negative, and the arrows pointing to the state become positive. This leads to the following three differential equations for the object in question (Figure 3):

$$\begin{cases} \frac{dP_0(\mathrm{t})}{dt} = -\left(\lambda_r + \lambda_d\right) \cdot P_0(\mathrm{t}) + \mu \cdot P_1(\mathrm{t}) \\ \frac{dP_1(\mathrm{t})}{dt} = \lambda_r \cdot P_0(\mathrm{t}) - \mu \cdot P_1(t) \\ \frac{dP_2(\mathrm{t})}{dt} = \lambda_d \cdot P_0(\mathrm{t}) \end{cases} \quad (1)$$

Since the electric motor in question can always be located only in one of three different states, the sum of the probabilities of its being in these states at any time of operation is equal to one. With this in mind, we can write the following normalizing condition:

$$P_0(t) + P_1(t) + P_2(t) = 1 \quad (2)$$

Since at the time of the start of operation, the electric motor is usually in the operable state, the initial conditions can be recorded:

$$P_0(0) = 1 \text{ and } P_i(0) = 0, \text{ for } i = 1, 2 \quad (3)$$

In order to determine the state probabilities of the object, it is necessary to solve the system of differential equations (1), taking into account the normalization and initial conditions (2–3).

As mentioned above, the system of differential equations (1) can be solved numerically. If the number of states is not too large, such problems can also be solved analytically, for example using the Laplace transform.

Let $\tilde{P}_i(s)$ denote the Laplace transform of the state probabilities $P_i(t)$. Then, the following can be written:

$$L\left[P_i(t)\right] = \tilde{P}_i(s) = \int_0^{\infty} P_i(t) \cdot e^{-st} dt \quad (4)$$

Applying the Laplace transform and taking into account the initial conditions (3), the system of equations of state (1) is mapped as follows:

$$\begin{cases} s \cdot \tilde{P}_0(s) - 1 = -(\lambda_r + \lambda_d) \cdot \tilde{P}_0(s) + \mu \cdot \tilde{P}_1(s) \\ s \cdot \tilde{P}_1(s) = \lambda_r \cdot \tilde{P}_0(s) - \mu \cdot \tilde{P}_1(s) \\ s \cdot \tilde{P}_2(s) = \lambda_d \cdot \tilde{P}_0(s) \end{cases} \quad (5)$$

If we express the probabilities $\tilde{P}_1(s)$ and $\tilde{P}_2(s)$ from the last two equations of the system by $\tilde{P}_0(s)$, we can write:

$$\begin{cases} \tilde{P}_1(s) = \frac{\lambda_r}{s + \mu} \cdot \tilde{P}_0(s) \\ \tilde{P}_2(s) = \frac{\lambda_d}{s} \cdot \tilde{P}_0(s) \end{cases} \quad (6)$$

Substituting these expressions in the first equation of the system (5), we can write:

$$\tilde{P}_0(s) \cdot \left[s + \lambda_r + \lambda_d - \frac{\mu \cdot \lambda_r}{s + \mu} \right] = 1$$

Or

$$\tilde{P}_0(s) = \frac{s + \mu}{s^2 + s(\lambda_r + \lambda_d + \mu) + \lambda_d \cdot \mu} \quad (7)$$

The denominator of the last expression can also be written as follows:

$$\tilde{P}_0(s) = \frac{s + \mu}{(s - \alpha)(s - \beta)} \quad (8)$$

Here the numbers α and β are the roots of the quadratic equation $s^2 + s(\lambda_r + \lambda_d + \mu) + \lambda_d \mu = 0$.

$$\alpha = \frac{-(\lambda_r + \lambda_d + \mu) + \sqrt{(\lambda_r + \lambda_d + \mu)^2 - 4\lambda_d \cdot \mu}}{2};$$

$$\beta = \frac{-(\lambda_r + \lambda_d + \mu) - \sqrt{(\lambda_r + \lambda_d + \mu)^2 - 4\lambda_d \cdot \mu}}{2}$$

For the reverse transformation, (7) is transformed in the following way

$$\tilde{P}_0(s) = \frac{M}{s-\alpha} + \frac{N}{s-\beta} \qquad (9)$$

The parameters M and N are included here to simplify calculations:

$$M = \frac{\mu+\alpha}{\alpha-\beta}; \; N = \frac{\mu+\beta}{\beta-\alpha}$$

Thus, by applying the inverse transformation to expression (9), using the Laplace transform for elementary functions according to (Bronshteinet al., 2015), we will be able to determine the dependence of the survival probability of electric motor on time:

$$P_0(t) = M \cdot e^{\alpha t} + N \cdot e^{\beta t} \qquad (10)$$

To determine the probabilities $P_1(t)$ and $P_2(t)$, it is necessary to perform an inverse transformation operation taking into account expression (9) in equations (5). For this purpose, we use expressions of Laplace transformations of elementary functions based on (Bronshteinet al., 2015):

$$P_1(t) = \frac{\lambda_r \cdot M}{\mu+\alpha}(e^{\alpha t} - e^{-\mu \cdot t}) + \frac{\lambda_r \cdot N}{\mu+\beta} e^{\beta t} - e^{-\mu \cdot t} \qquad (11)$$

$$P_2(t) = \frac{\lambda_d \cdot M}{\alpha}(e^{\alpha t} - 1) + \frac{\lambda_d \cdot N}{\beta}(e^{\beta t} - 1) \qquad (12)$$

Reliability analysis of a drive system consisting of two or more components

The drive systems of sucker-rod pumps consist of two or more components; therefore, the reliability of the entire system, according to the maintainability criterion, is of particular interest. Failures that occur in the drive during operation can usually be eliminated through repair work. However, as a result of random events – such as design and production errors, human errors, or other unforeseen factors – failures may occur that cannot be eliminated. In addition, after prolonged operation, many components of the transmission system often fail due to wear and fatigue, causing the system to lose its operability. In such cases, restoring the drive unit through repair becomes economically unfeasible, and the unit is completely decommissioned. Therefore, for a more accurate assessment of system reliability, it is important to take unrecoverable failures into account. Furthermore, an accurate assessment of reliability indicators is crucial for improving equipment availability and ensuring the efficient supply of spare parts.

First, let's look at the drive system, which consists of two components. The paper by Abdullayev and Chalabi (2020), examines the issue of assessing the reliability of the gear motor system was considered, taking into account only recoverable failures. Since the transmission mechanism of a sucker-rod pump usually consists of a gearbox and a belt drive, we consider the reliability estimates of this two-component system. Cases of complete withdrawal from service of the transmission mechanism (Figure 4a) as a result of total failures cannot be excluded. Figure 4b shows a description of the Markov model, also taking into account the unrecoverable failures of the transmission mechanism. It also considers the possibility that gearbox failure could cause certain belt-drive malfunctions. In operation, such a case occurs quite often. The blocking or the vibrations that arise due to the failure of the gearbox (tooth breakage, pitting, wear, etc.) can also subsequently cause the failure of the belt drive. The failure rate λ_1 and the repair rate μ_1 describe the transitional behaviour of the belt drive, while the rates λ_2 and μ_2 describe that of the gearbox. The rate λ_3 describes the belt-drive failure as a result of the gearbox failure, and the rate μ_3 describes the repair process of both components together. The failure rate λ_4 describes the transitional behaviour of the system toward the depreciation state due to unrecoverable total failure or aging. The failure rates depend mainly on the design quality and operating conditions, while the repair rates depend on the structure and level of repair work. The states that the transmission system in question can assume during its life cycle, and their corresponding probabilities, are shown in Table 1.

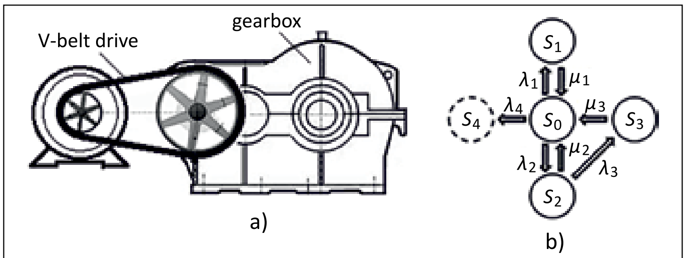

Figure 4. The transmission system of sucker-rod pumps consists of two components (a) and related Markov state graph (b)

Table 1. The states of transmission system and corresponding probabilities

State	Description of the states	State probability
S_0	Both components are intact	$P_0(t)$
S_1	The V-belt drive is faulty, the gearbox is intact	$P_1(t)$
S_2	The V-belt drive is intact, the gearbox is faulty	$P_2(t)$
S_3	Both components are defective, subject to repair	$P_3(t)$
S_4	The system has been completely decommissioned	$P_4(t)$

Kolmogorov differential equations based on the presented Markov model for the transmission system can be written as follows:

$$\begin{cases} \frac{dP_0(t)}{dt} - (\lambda_1 + \lambda_2 + \lambda_4) \cdot P_0(t) + \mu_1 \cdot P_1(t) + \mu_2 \cdot P_2(t) + \mu_3 \cdot P_3(t) \\ \frac{dP_1(t)}{dt} = \lambda_1 \cdot P_0(t) - \mu_1 \cdot P_1(t) \\ \frac{dP_2(t)}{dt} = \lambda_2 \cdot P_0(t) - (\mu_2 + \lambda_3) \cdot P_2(t) \\ \frac{dP_3(t)}{dt} = \lambda_3 \cdot P_2(t) - \mu_3 \cdot P_3(t) \\ \frac{dP_4(t)}{dt} = \lambda_4 \cdot P_0(t) \end{cases} \quad (13)$$

Since the transmission system can accept only one of the states indicated in Table (1) at any time during operation, we can write the following condition:

$$P_0(t) + P_1(t) + P_2(t) + P_3(t) + P_4(t) = 1 \quad (14)$$

Considering that at the time of the start of operation both components of the transmission system are intact, the initial conditions can be written as follows:

$$P_0(0) = 1 \text{ and } P_i(0) = 0, \text{ for } i = 1,2,3,4 \quad (15)$$

Tschalabi's paper (2020), an assessment of the reliability of a drive system consisting of three components was considered. The drives of sucker-rod pumps often consist of four or more components. For example, the drive of sucker-rod pump shown in Figure 1 consists of four different components: motor, V-belt drive, gearbox and double four-bar mechanism. Given the harsh operating conditions of the drive, it can be assumed that total unrecoverable failures of the drive are also one of the cases encountered in practice. With this in mind, it is possible to describe the Markov model of the four-component system in question in accordance with Figure 5. Here, the state S_5 corresponds to the impossibility of restoring the system, the probability of occurrence of this state is denoted by $P_5(t)$, and the failure rates of the system that cannot be eliminated are denoted by λ_5.

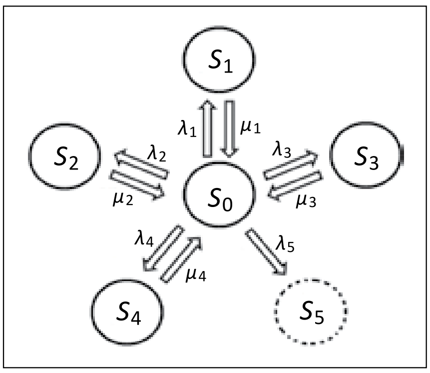

Figure 5. Markov model for drive of sucker-rod pumps

For simplicity of calculations, the components of the system are assumed to be independent. Kolmogorov's system of differential equations based on the presented Markov model for the considered four-component system can be written as follows:

$$\begin{cases} \frac{dP_0(t)}{dt} - (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5) \cdot P_0(t) + \mu_1 \cdot P_1(t) + \\ \qquad + \mu_2 \cdot P_2(t) + \mu_3 \cdot P_3(t) + \mu_4 \cdot P_4(t) \\ \frac{dP_1(t)}{dt} = \lambda_1 \cdot P_0(t) - \mu_1 \cdot P_1(t) \\ \frac{dP_2(t)}{dt} = \lambda_2 \cdot P_0(t) - \mu_2 \cdot P_2(t) \\ \frac{dP_3(t)}{dt} = \lambda_3 \cdot P_0(t) - \mu_3 \cdot P_3(t) \\ \frac{dP_4(t)}{dt} = \lambda_4 \cdot P_0(t) - \mu_4 \cdot P_4(t) \\ \frac{dP_5(t)}{dt} = \lambda_5 \cdot P_0(t) \end{cases} \quad (16)$$

Since the drivesystem can accept only one of the states indicated in Figure 5 at any time of operation, we can write the following condition:

$$\sum_{i=1}^{5} P_i(t) = 1, \text{ for } i = 1,2,3,4,5 \quad (17)$$

Assuming that all drive components are fully operational at the start of operation, the initial conditions can be expressed as follows:

$$P_0(0) = 1 \text{ and } P_i(0) = 0, \text{ for } i = 1,2,3,4,5 \quad (18)$$

Materials and methods

A heterogeneous Markov model was used to analyze the reliability of a separate component of sucker-rod pumps. Graphs of the Markov process and the corresponding Kolmogorov differential equations were compiled. The system of differential equations (1) was solved analytically using the Laplace transform. This approach can be applied for each individual component of sucker-rod pumps, for example, for an electric motor, gearbox, etc. Here, the normalizing condition (2) and the initial conditions (3) are taken into account. The obtained formulas (10–12) allow the probability of the state occupied by thecomponent to be determined at any given time. However, this requires knowledge of the failure and recovery rates, which can be obtained during operation based on statistical data on failures and repairs (Chalabi, 2021). Using the presented methodology, the state probabilities of the electric motor are calculated for a recoverable failure rate of $\lambda_r = 0.5$ year^{-1} and a recovery rate of $\mu = 1$ year^{-1}, considering different values of the unrecoverable failure rate. The results of these calculations are shown in Figures 6 and 7. At first, the calculations were performed without taking into account unrecoverable failures, taking $\lambda_d = 0$ (Figure 6). And then the calculations were carried out taking into account unrecoverable failures, taking $\lambda_d = 0.1$ year^{-1} (Figure 7). As can be seen from these figures, the reliability of an electric motor largely depends on the intensity of the unrecoverable failures.

Therefore, to more accurately assess the demand for spare parts, it is essential to account for the unrecoverable failures of the electric motor.

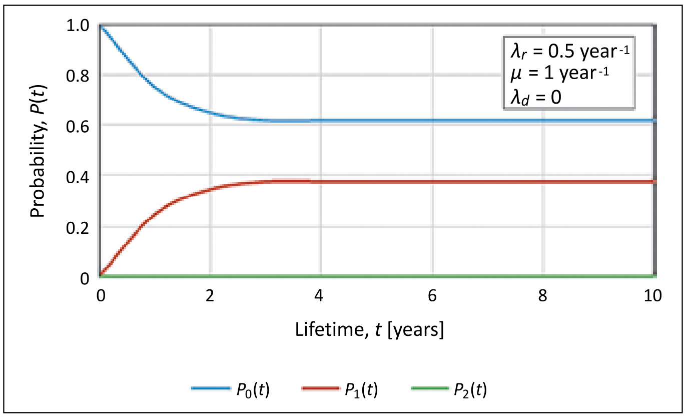

Figure 6. State probabilities of the electric motor without consideration of unrecoverable failures

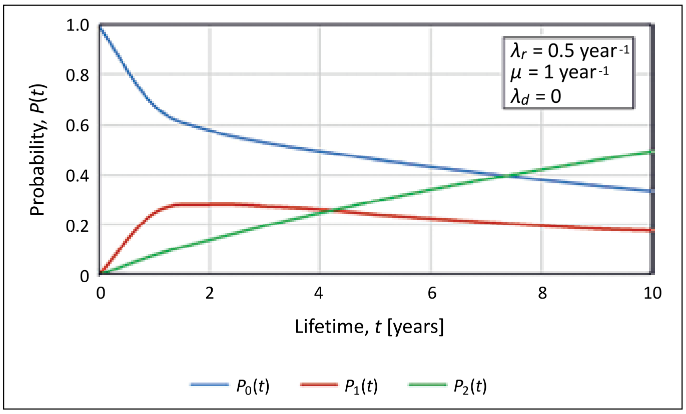

Figure 7. State probabilities of the electric motor with consideration of unrecoverable failures

Analytical solution of the system of differential equations (13) using the Laplace transform involves complex mathematical operations. Therefore, considering condition (14) and the initial conditions (15), the system was solved using MATLAB. The solver ode45 was used to solve this ordinary system of differential equations, as it is more efficient for solving such a problem. The adaptive Runge–Kutta–Fehlberg/Dormand–Prince method of order 4(5) is implemented here. For the period of operation $t = 7$ years, the probabilities of states were determined, without taking into account (Case 1: $\lambda_4 = 0$) and taking into account (Case 2: $\lambda_4 = 0.1$ year^{-1}) the impact of unrecoverable failures. The following program was used for this purpose:

Case 1: $\lambda_4 = 0$:

```
clear;clc
lambda1=0.2;lambda2=0.3;lambda3=2;mu1=2;mu2=2;mu3=1;
dpdt=@(t,x) [-(lambda1+lambda2)*x(1)++mu1*x(2)+mu2*x(3)+mu3*x(4);
   lambda1*x(1)-mu1*x(2);lambda2*x(1)-(mu2+lambda3)*x(3);
   lambda3*x(3)-mu3*x(4)];
[t,x]=ode45(dpdt,[0 7],[1 0 0 0]);
% ode45(dpdt,[0 7],[1 0 0 0]);
plot(t,x(:,1),'r',t,x(:,2),'k-',t,x(:,3),'--',t,x(:,4),'k-.')
legend('P0(t)','P1(t)','P2(t)','P3(t)')
xlabel('lifetime,t(year)')
ylabel('Probability,Pi(t)')
grid on
check_prob=sum(x,2);
```

Case 2: $\lambda_4 = 0.1$ year^{-1}:

```
clear;clc
lambda1=0.2;lambda2=0.3;lambda3=2;mu1=2;mu2=2;mu3=1;lambda4=0.1;
dpdt=@(t,x)[-(lambda1+lambda2+lambda4)*x(1)+mu1*x(2)+mu2*x(3)+mu3*x(4);
   lambda1*x(1)-mu1*x(2);lambda2*x(1)-(mu2+lambda3)*x(3);
   lambda3*x(3)-mu3*x(4);lambda4*x(1)];
[t,x]=ode45(dpdt,[0 7],[1 0 0 0 0]);
% ode45(dpdt,[0 7],[1 0 0 0 0]);
```

```
plot(t,x(:,1),'r',t,x(:,2),'k-',t,x(:,3),'.',t,x(:,4),'k.',t,x(:,5),'*')
legend('P0(t)','P1(t)','P2(t)','P3(t)','P4(t)')
xlabel('lifetime,t(year)')
ylabel('Probability,Pi(t)')
grid on
check_prob=sum(x,2);
```

The time-dependent probabilities of the system states, accounting for unrecoverable failures at various failure and repair rates of the transmission system and its main components, are shown in Figures 8 and 9. In the first case, the calculations were performed without taking into account unrecoverable failures, assuming μ_1 = 2 year^{-1}, μ_2 = 2 year^{-1}, μ_3 = 1 year^{-1}, λ_1 = 0.2 year^{-1}, λ_2 = 0.3 year^{-1}, λ_3 = 2 year^{-1} and λ_4 = 0 (Figure 8). In the second case, the calculations were carried out taking into account unrecoverable failures, assuming λ_4 = 0.1 year^{-1} (Figure 9). As can be seen from these figures, the reliability of the system largely depends on the intensity of the unrecoverable failures, λ_d.

Similar calculations were performed for a four-component drive of sucker-rod pumps (Figures 1 and 5). Numerically solving the system of equations (16) using MATLAB and the ode45 solver, graphs of the probability of the drive states at different values of λ_5 were built (Figure 10 and 11). In the first case, the calculations were performed without taking into account

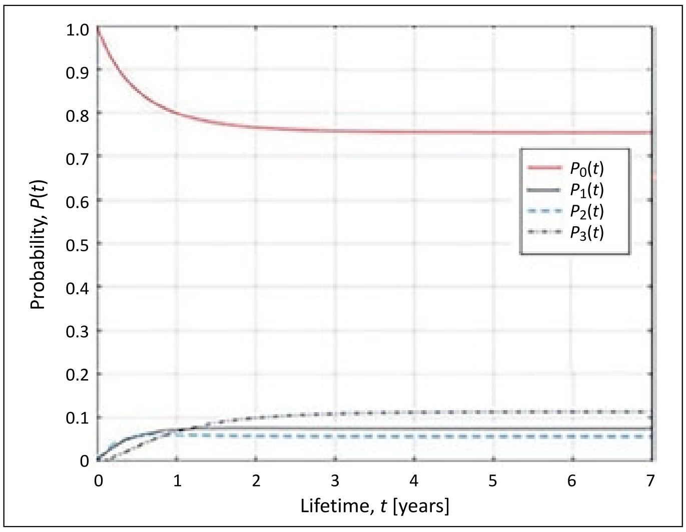

Figure 8. State probabilities of the transmission system without consideration of unrecoverable failures

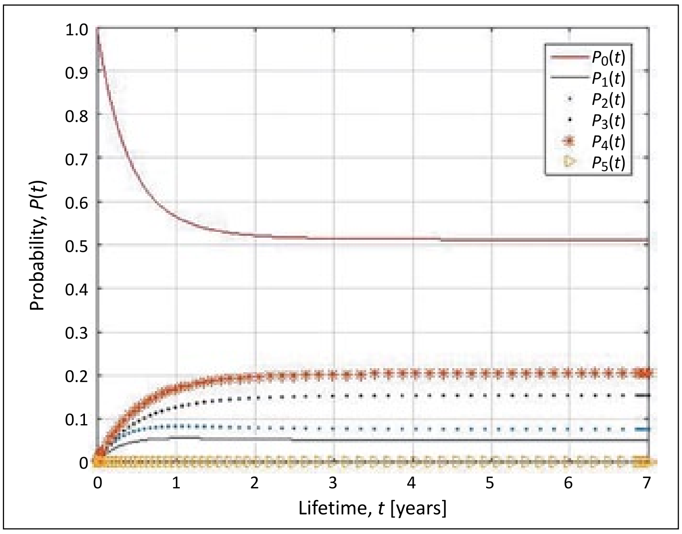

Figure 10. State probabilities of the drive of sucker-rod pumps without consideration of unrecoverable failures

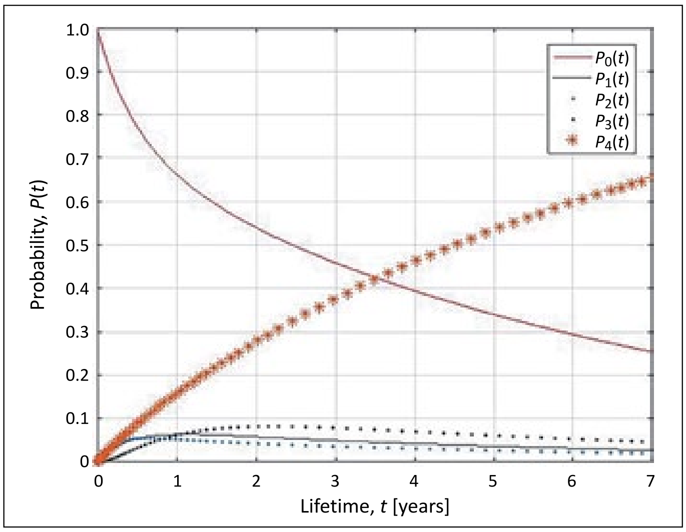

Figure 9. State probabilities of the transmission system with consideration of unrecoverable failures

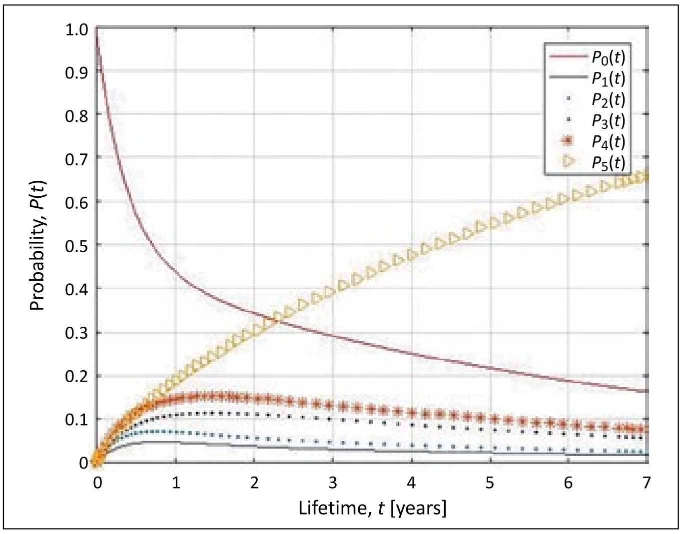

Figure 11. State probabilities of drive of sucker-rod pumps with consideration of unrecoverable failures

unrecoverable failures, assuming $\mu_1 = 2$ year^{-1}, $\mu_2 = 2$ year^{-1}, $\mu_3 = 1$ year^{-1}, $\mu_4 = 1$ year^{-1}, $\lambda_1 = 0.2$ year^{-1}, $\lambda_2 = 0.3$ year^{-1}, $\lambda_3 = 0.3$ year^{-1}, $\lambda_4 = 0.4$ year^{-1} and $\lambda_5 = 0$ (Figure 10). In the second case, the calculations were carried out taking into account unrecoverable failures, assuming $\lambda_5 = 0.3$ year^{-1} (Figure 11). As can be seen from the graphs, the reliability of the winch drive system consisting of four components also depends on unrecoverable failures.

Results and discussion

Analysis of the results indicates that unrecoverable failures have a significant impact on the reliability of the drive of sucker-rod pumps and their components. Most importantly, the system's availability factor gradually decreases over time, which has critical implications for ensuring the timely supply of spare parts.

The obtained graphs show that with traditional methods of assessing the reliability of restored technical systems, the availability coefficient remains constant after some time of operation. But based on a new approach to assessing the reliability of recoverable systems, it is proved that, in fact, the availability is gradually decreasing due to non-recoverable failures. Therefore, for a more correct assessment of spare components, it is necessary to take into account failures that cannot be eliminated.

According to Babayev et al. (2015), the number of spare parts can be determined depending on the failure rate as follows:

$$a = nN\lambda T \tag{19}$$

where N is the number of equipment that requires spare parts; n is the number of components of the same type in the equipment; λ is the failure rate of the component in question; T is the lifetime of the equipment.

Using the example of an electric motor of drive of sucker-rod pumps, we will perform a comparative calculation of the required stock. Let's assume that the number of sucker-rod pumps in operation is $N = 50$. The number of electric motors in one equipment is $n = 1$. We take $\lambda_d = 0.1$ year^{-1} as in the example above. Then, according to formula (19), for the service life $T = 10$ years, we get $a = 50$. However, the number of electric motors under repair is at $\lambda_r = 0.5$ year^{-1} $a_r = 500$.

Conclusions

Traditional methods of assessing the reliability of technical systems do not take into account failures that cannot be eliminated. This does not allow for correctly assessing the need for replacements of the technical system as a whole or its individual components in case of total failures. Most of the failures that occur during the operation of the sucker-rod pump drive are eliminated by carrying out repair work. However, sometimes there may be total failures of the entire system or its individual components, which cannot be eliminated for technical or economic reasons. Unrecoverable failures of the sucker-rod pump drive system and its individual components have a significant impact on their reliability and do not allow maintaining a stable availability factor, which leads to its gradual decrease. Calculations show that due to unaccounted for unrecoverable failures, the availability factor can decrease by about 15-20% annually. Therefore, for a more correct assessment of reliability indicators and inventory requirements, it is important to take into account failures that cannot be eliminated.

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